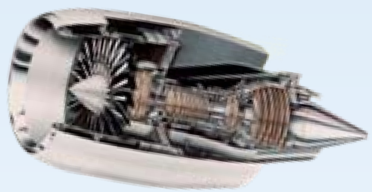
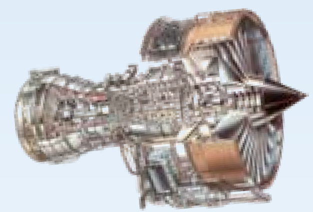
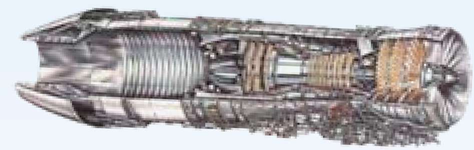
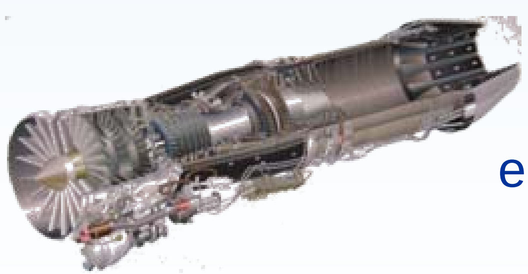
Distributed Engine Control







Workshop at Ohio Aerospace Institute, Cleveland OH
Nov. 6-7, 2007



Dennis Culley
Ph: (216) 433-3797
email: dennis.e.culley@nasa.gov
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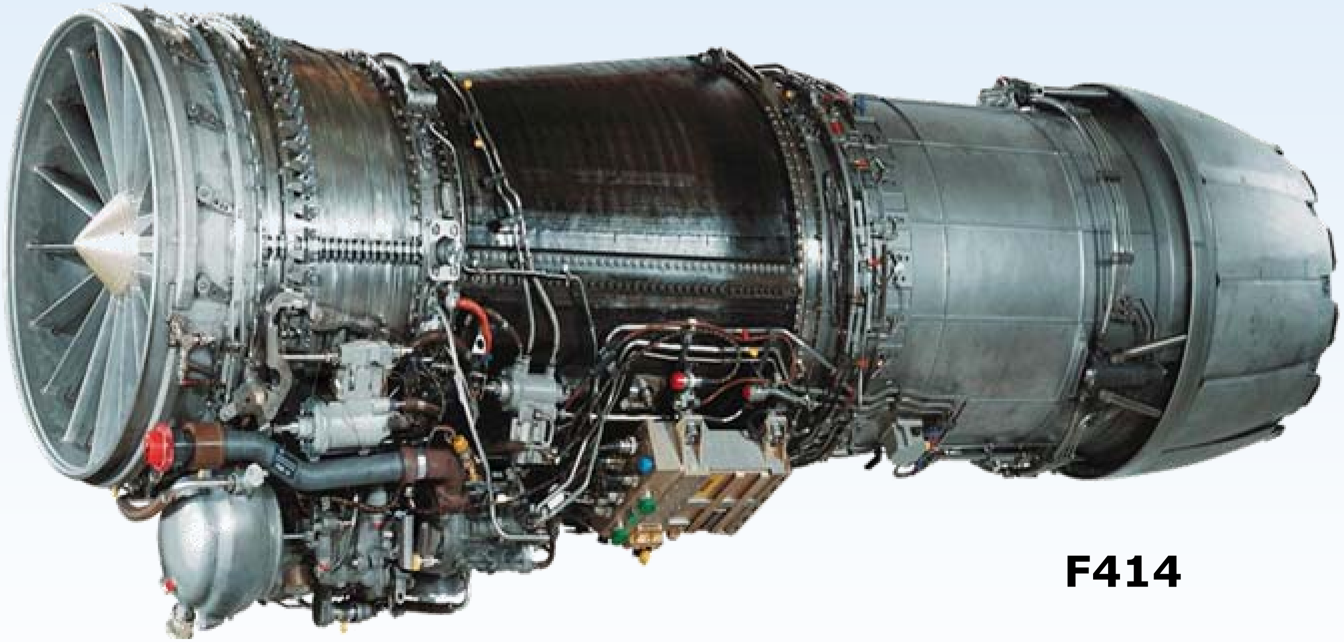
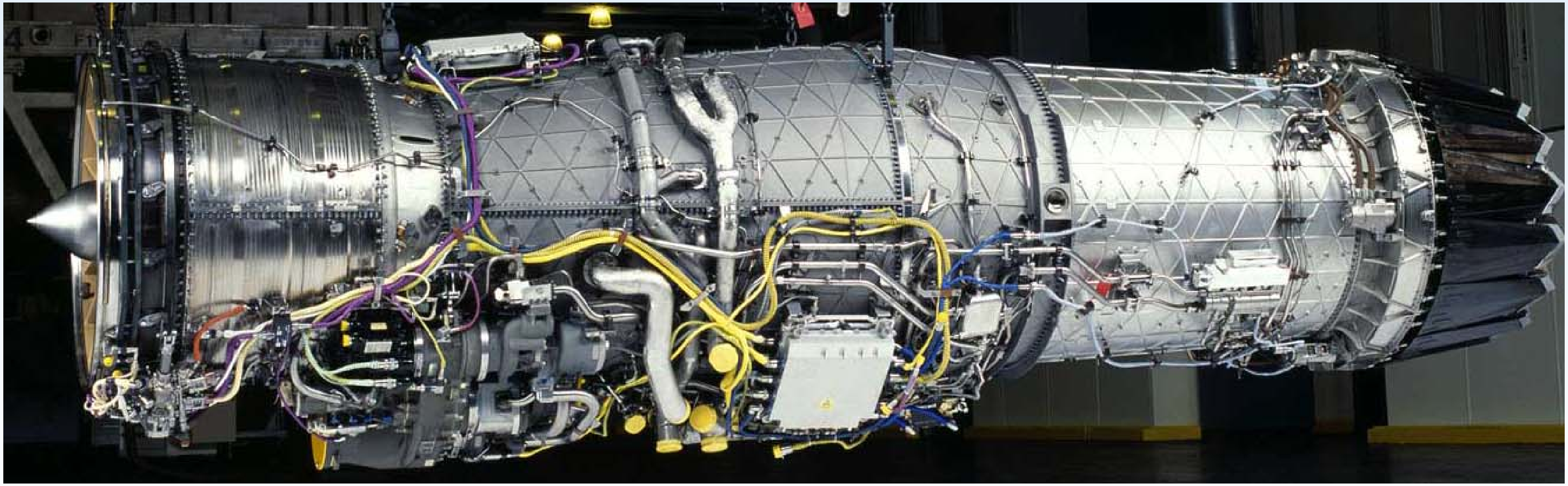
Can We Improve On This?



F414

Or How About This?



F135

Outline

- Team Members
- Focus & Expectations for Distributed Engine Control
- Overview of Distributed Engine Control Architecture
- Challenges of Distributed Engine Control
- NASA Task Plan Details
  - Architecture
  - Subsystems
  - High Temperature Electronics

Team Members

Dennis Culley	Controls & Dynamics (RIC)
Randy Thomas	Controls & Dynamics (RIC)
Joseph Saus	Controls & Dynamics (RIC)
Michael Krasowski	Optical Instrumentation and NDE (RIO)
Lawrence Greer	Optical Instrumentation and NDE (RIO)
Norman Prokop	Optical Instrumentation and NDE (RIO)
Glenn Beheim	Sensors and Electronics (RIS)
Laura Evans	Sensors and Electronics (RIS)
Philip Neudeck	Sensors and Electronics (RIS)
Richard Patterson	Space Environmental Durability (RPY)
Kue Chun	Digital Communications (RCD)
Joseph Flatico	Ohio Aerospace Institute (OAI)
Andrew Trunek	Ohio Aerospace Institute (OAI)
David Spry	Ohio Aerospace Institute (OAI)
Carl Chang	Arctic Slope Regional Corp (ASRC)

SFW.2.08—Controls and Dynamics

Enabling advanced aircraft configurations such as "Blended Wing Body (BWB)," "Extreme Short Take Off and Landing (ESTOL)" and **high performance "Intelligent Engines" will require advancement in the state of the art of dynamic modeling and flight/propulsion control**. Control methods need to be developed and validated for "optimal" and reliable performance of complex, unsteady, and nonlinear systems with significant modeling uncertainties. The **emphasis will be on developing technologies for** improved aircraft performance, enabling robust control of unconventional configurations, and **active control of components for improved propulsion efficiency and lower emissions**.

For enabling "Intelligent Engines," the focus will be on developing technologies for enabling distributed engine control to **reduce overall controls and accessories weight** for the propulsion system and **increase control system reliability**.

Expectations for Distributed Engine Control

Improve Engine Performance

Reduce Engine Life Cycle Cost

Reduce Time to Design/Modify Engine Control System

Performance Metrics

Reduce Engine Weight

- by reducing the weight of control components but also by enabling the implementation of other new control technologies which effect engine weight reduction

Improve Control System Accuracy and Responsiveness

- by improving long-term sensor and actuator accuracy, enabling the availability of more system information, improving loop responsiveness with local control

Increase System Availability

- by adapting to system aging effects and isolating faults

Engine Life-Cycle Cost Metrics

Reduce Design, Manufacture, Integration and Test Costs

- by using functional modularity and standardization to create common building blocks within engine systems and across engine platforms – helps primes, suppliers, and certification

Reduce Operational Costs

- by reducing fuel consumption through better efficiency, reducing the need for scheduled maintenance, and increasing system availability

Reduce Logistical Costs

- by reducing the part inventories, reducing obsolescence, and reducing training requirements

Design/Modify Time Metrics

Initial Design Cycle

- by providing a set of functional building blocks which are common across engines and engine platforms

Planned Design Modifications and Upgrades

- by providing a common interface which enables a clear upgrade path

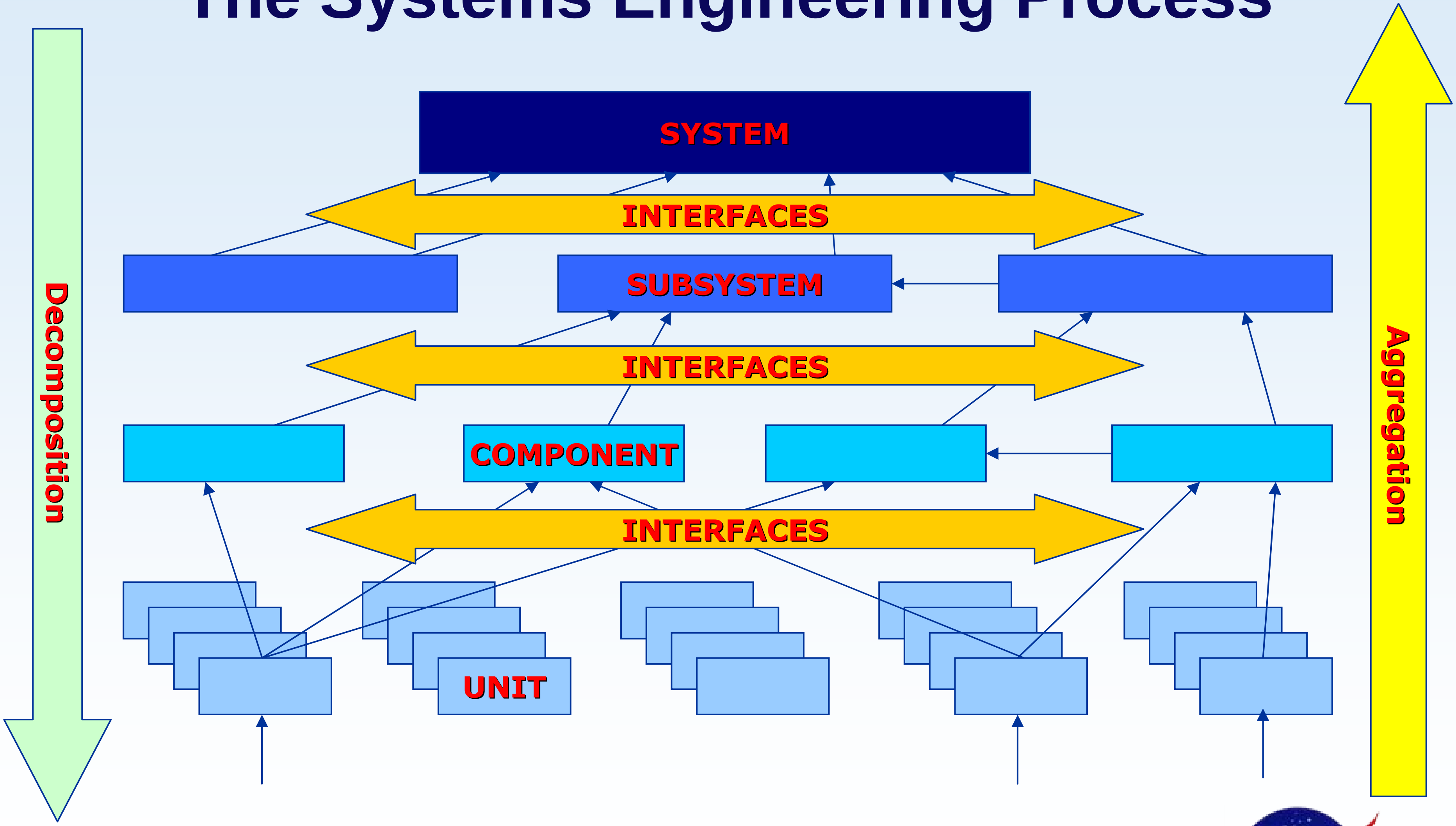
Unplanned Obsolescence

- by providing a means to isolate system implementation from system function – reducing the impact on existing systems

Overview of Distributed Engine Control

- Systems Engineering
- Vision
- Architecture - Evolutionary or Revolutionary?

The Systems Engineering Process



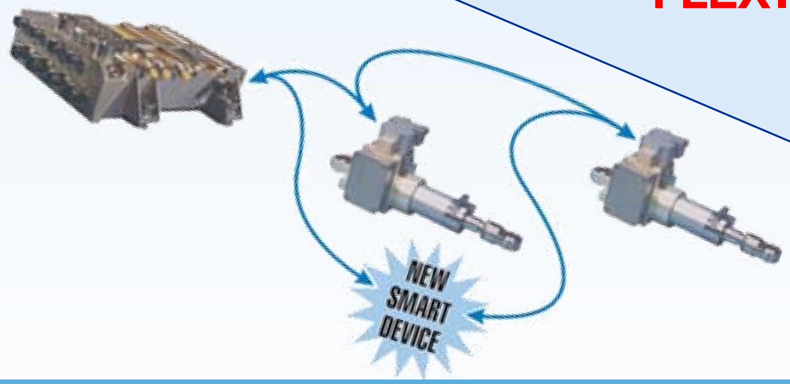
Vision for Distributed Control

Decomposition of the Engine Control Problem into **FUNCTIONAL ELEMENTS** results in **MODULAR** components. These components create the building blocks of any engine control system.

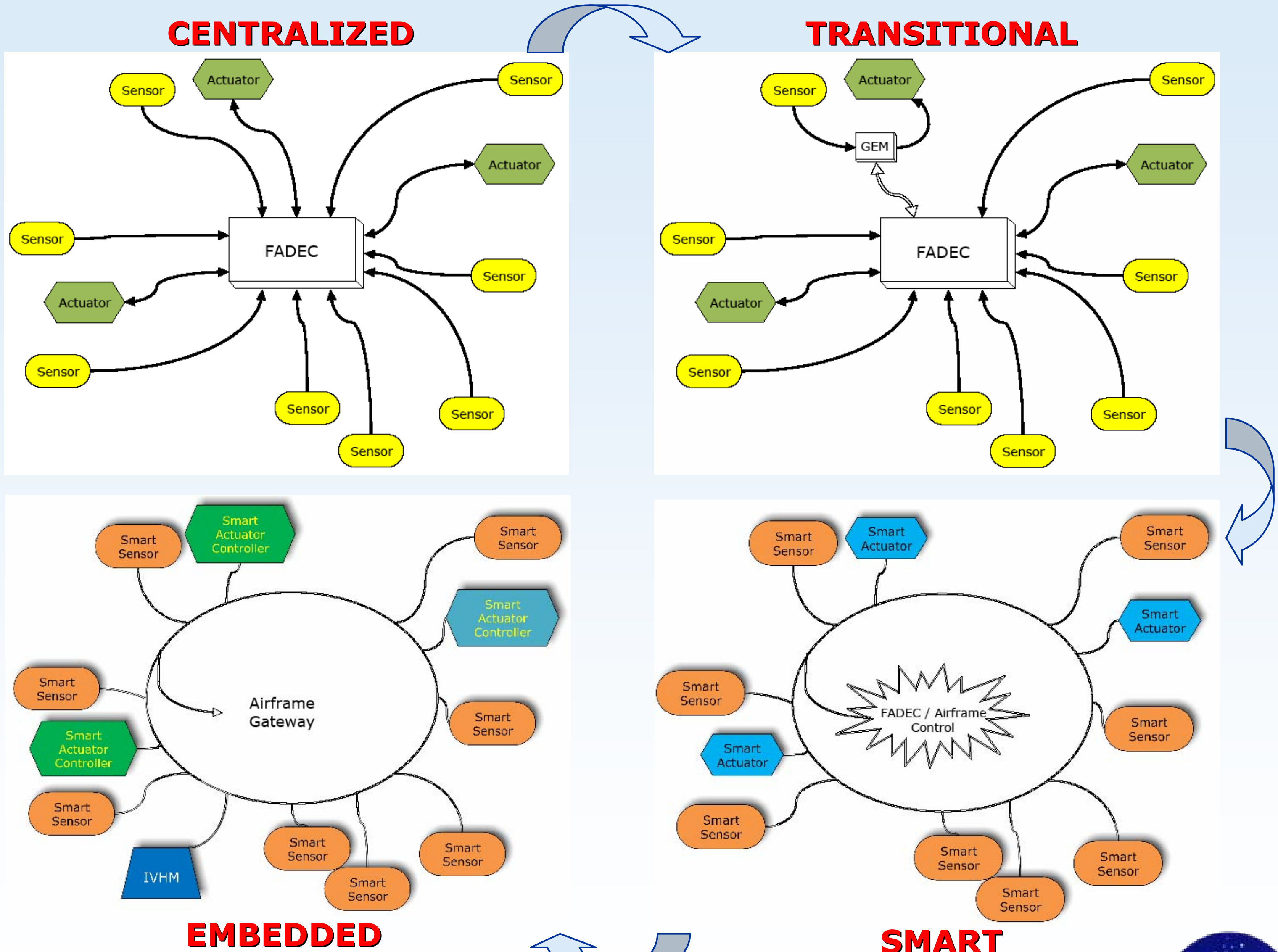
MODULARITY

- **COMMONALITY**
- **EXPANDIBILITY**
- **SCALABILITY**
- **FLEXIBILITY**

- **OBSOLESCENCE MITIGATION**
- **LOWER PROCESSING REQUIREMENTS**
- **ENHANCED PERFORMANCE**
- **LOWER WEIGHT**
- **REDUCED COST**



The use of **OPEN SYSTEM STANDARDS** enhances benefits by leveraging the greatest possible market for components .

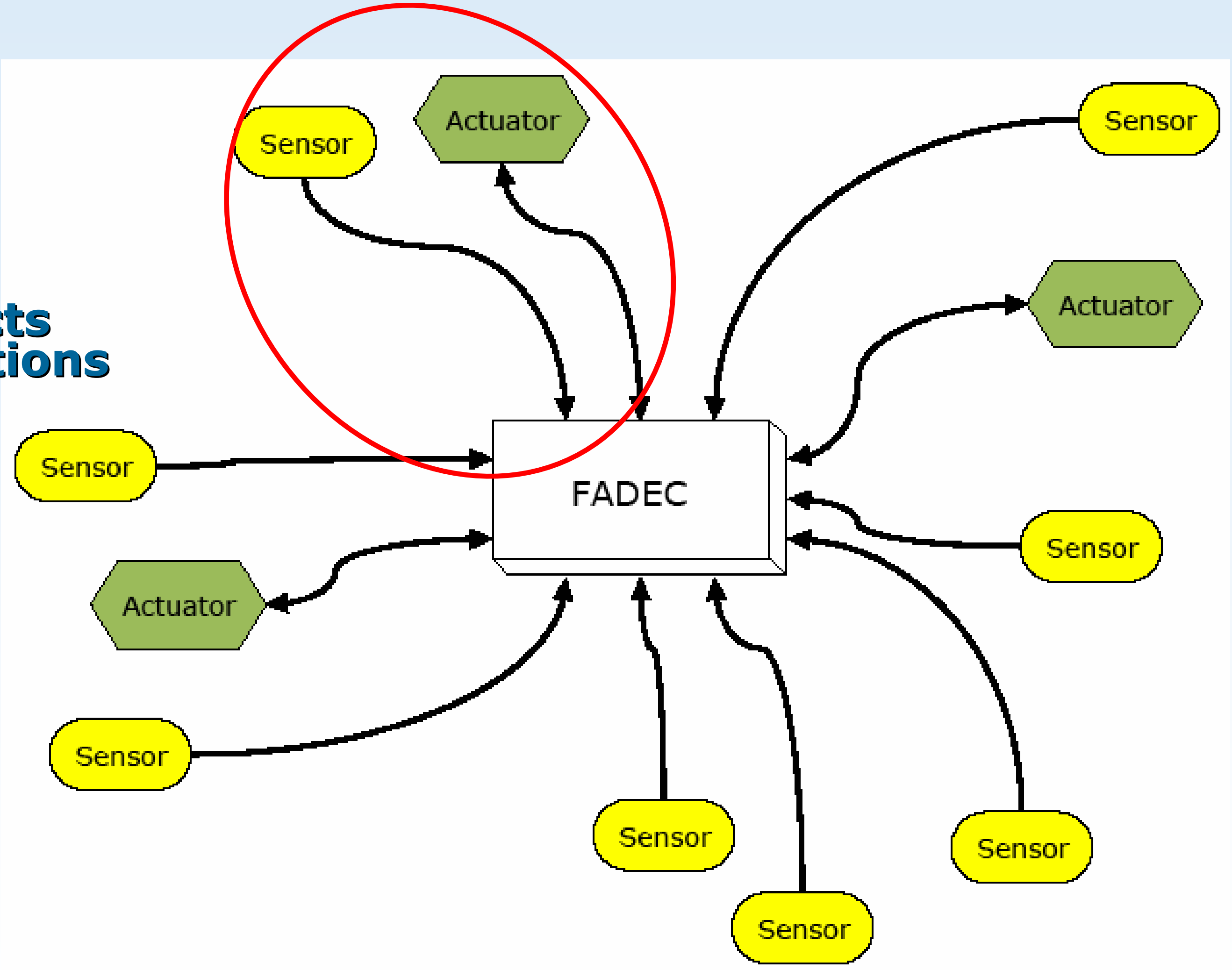

CENTRALIZED
TRANSITIONAL
EMBEDDED
SMART
Sensor
Actuator
FADEC
GEM
Smart Sensor
Smart Actuator Controller
Smart Actuator
Airframe Gateway
IVHM
FADEC / Airframe Control

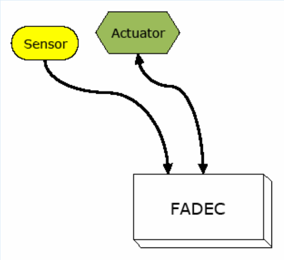
Centralized Architecture

FADEC

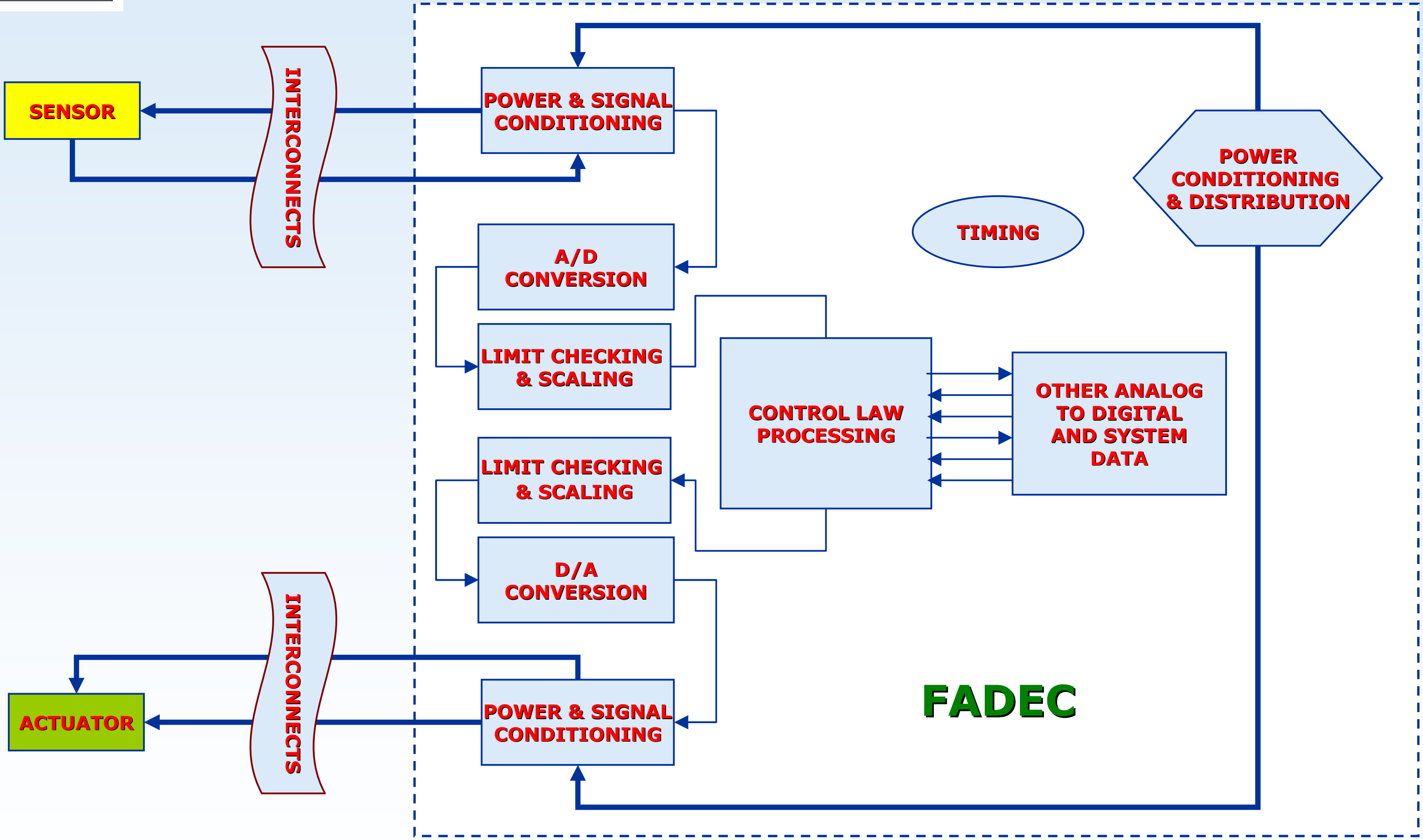
System Effectors

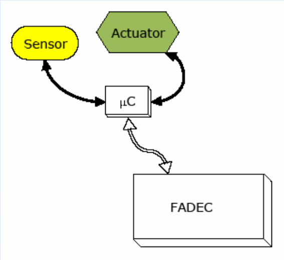
Interconnects & Communications



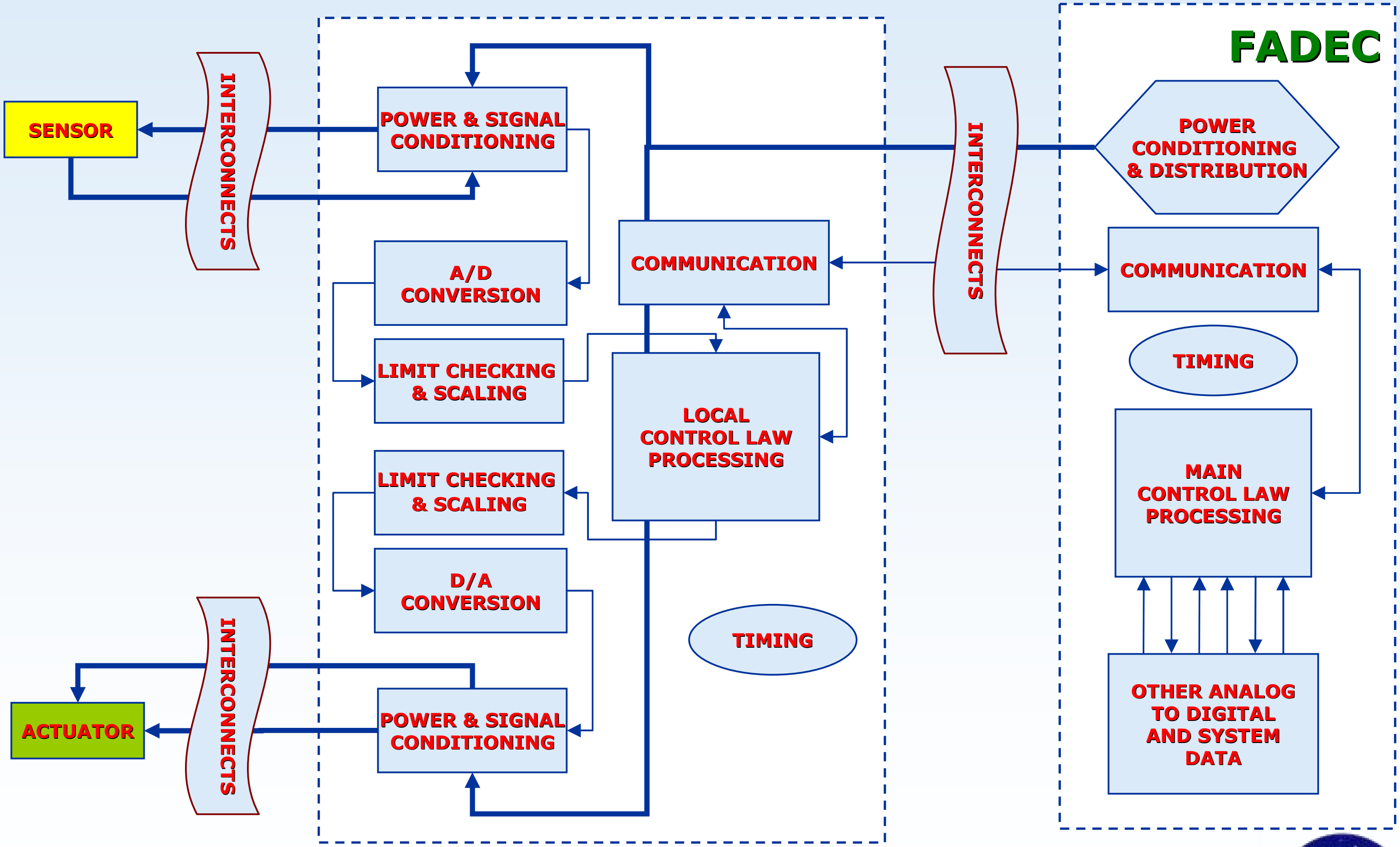


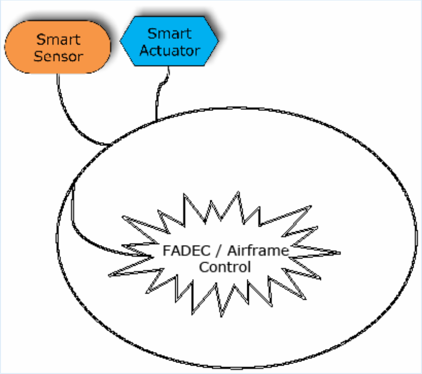
Centralized Functions



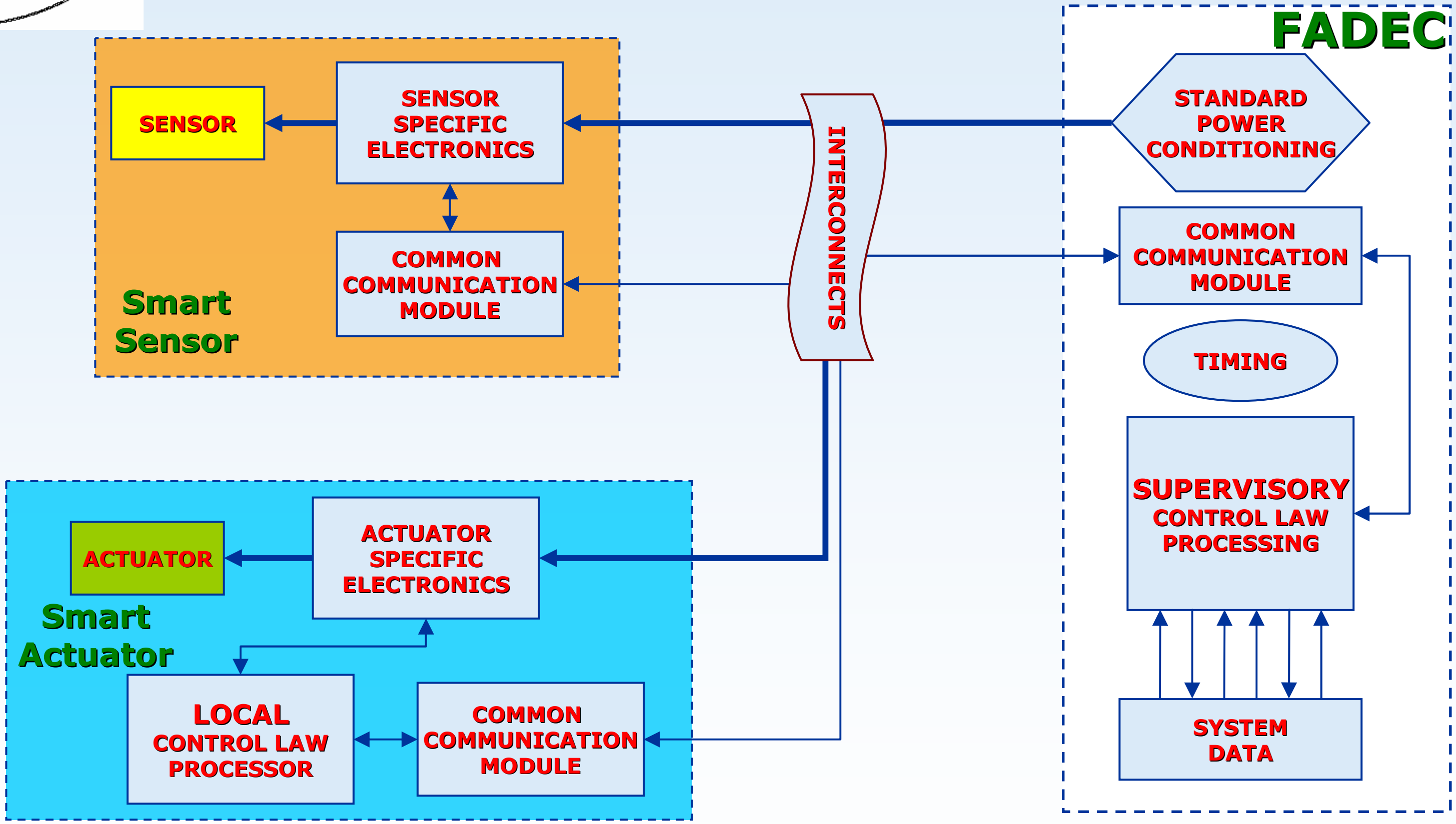


Transitional Functions

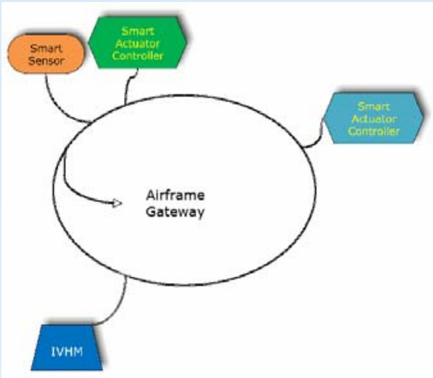


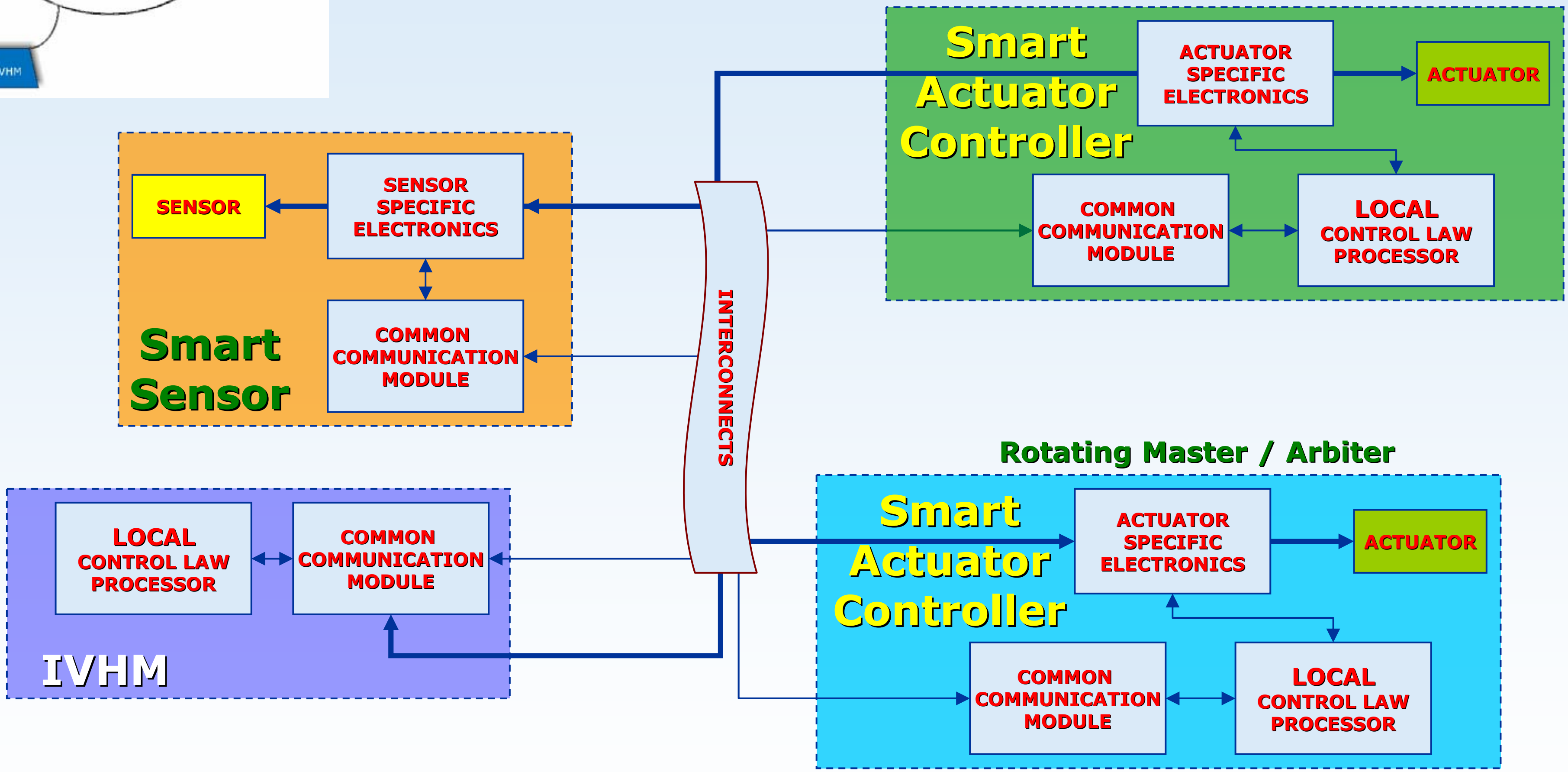


Smart Functions



Embedded Functions





Challenges of Distributed Engine Control

System Constraints

1. **Failure effects in a mission critical design.**
   a) Reliability
   b) Failure Modes
2. **Extreme environmental conditions.**
   a) Temperature
   b) Vibration, Shock
   c) Water, salt spray, hydrocarbon fuels, and cleaning solvents, altitude
   d) electromagnetic interference, susceptibility and control, lightning

Fixed

3. **Performance sensitivity to system weight.**
4. **Sensitivity to overall cost, including development, manufacture, operation, maintenance, and logistics.**

Business Decisions

Challenges of Distributed Engine Control

Tall Pole Technology Issues

High Temperature Electronics

- Mid-temperature environment (< 250 °C) using silicon on insulator (SOI): limited part selection, full engine temperature range far exceeds SOI capability
- High-temperature environment (< 500 °C) using silicon carbide (SiC): almost no commercially available parts, basic issues remain to be resolved

Robust, Deterministic Communications

- Industry standards exist, but not applied to aero-engine applications – Mission Critical
- Issues related to electronic parts availability at temperature and environmental conditions

Distributed Engine Control Task Plans

- Distributed Engine Control **Working Group** (DECWG)
- Distributed Engine Control **Architecture**
- Distributed Engine Control **Subsystems**
- **High Temperature Electronics and Sensors**

Distributed Engine Control Working Group

Dennis Culley
NASA Glenn Research Center

Alireza Behbahani
Air Force Research Laboratory

Richard Millar
Navy NAVAIR

Bert Smith,
Christopher Darouse
Army AATD

Bruce Wood
Jim Krodel
Pratt & Whitney

Sheldon Carpenter,
Bill Mailander
GE Aviation

Colin Bluish
Rolls-Royce North American Technologies Inc.

Bobbie Hegwood
Rolls Royce

John Teager,
Ronald Quinn
Honeywell

Gary Battestin,
Walter Roney
BAE SYSTEMS

William Rhoden
Hamilton Sundstrand

Bill Storey
Goodrich

Distributed Engine Control Working Group

The main goals of the DECWG

- Identify, quantify and validate **benefits** from the stakeholder perspective.
- Identify the impact of **new control strategies** on all facets of the user community; including design, fabrication, assembly, supply chain, and operations.
- Identify **regulatory and business barriers** which impede the implementation of alternate control philosophies.
- Identify existing and emerging **technologies** which can be leveraged in the aero-engine control system.
- Identify **technology barriers** which prevent the implementation of alternate control philosophies and provide guidance to industry for their removal.
- Develop an overall **roadmap** with which to guide the successful implementation of alternate control philosophies.

Distributed Control Architecture

Task Focus

- Analyze the potential benefits, especially for volume and weight reduction, due to system architecture and design
- Investigate the availability and application of open standards for engine control
- Explore the use and availability of commercial and military off-the-shelf (COTS / MOTS) hardware
- Identify emerging embedded hardware architectures and technologies that can be applied to aeropropulsion engine control

Path to a New FADEC

From F414 engine

From CFM56 engine

Transitioning from Centralized to Distributed engine control architecture changes the FADEC functionality and design

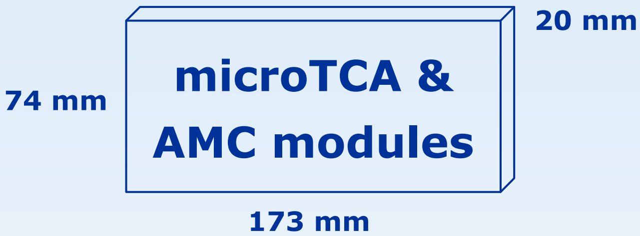
- Eliminates the need for analog data handling - represents ~50% volume reduction
- Significantly reduces the pin and connector count – a major source of weight, reliability issues, and integration issues
- Reduces the need to customize circuitry for a specific application – decreases cost and design/upgrade cycle time

New Technologies for Harsh Environment Computing

High performance computer hardware, in a small form factor, based on robust open standards, is being rapidly pursued by industry. At least two of these competing commercial platform specifications have potential for aeropropulsion control systems.

- **A small form factor is critical to address the shock and vibration environment on engine and airframe applications with minimal support structure, i.e., weight and volume**
- **Conduction cooled hardware is critical to address the high power density of small form factor modules and the lack of convection cooling in engine-mounted applications**

Small Form-Factor Computing



The Advanced Mezzanine Card (AMC) is a small form-factor, hot-swappable module originally developed for high bandwidth telecommunications systems and are supported by a large industrial base. The Micro Telecommunications Computing Architecture (MicroTCA) specification leverages the AMC form-factor and support while creating a new, low-cost, flexible, high-bandwidth and highly scalable small form-factor computing platform.

Standard organization: PICMG

Standard: microTCA.0

VPX, a descendent of the VMEbus legacy delivers state-of-the-art computing performance to high-end embedded computing applications. VPX offers complete electrical and dimensional compatibility with a large, existing base of VME products.

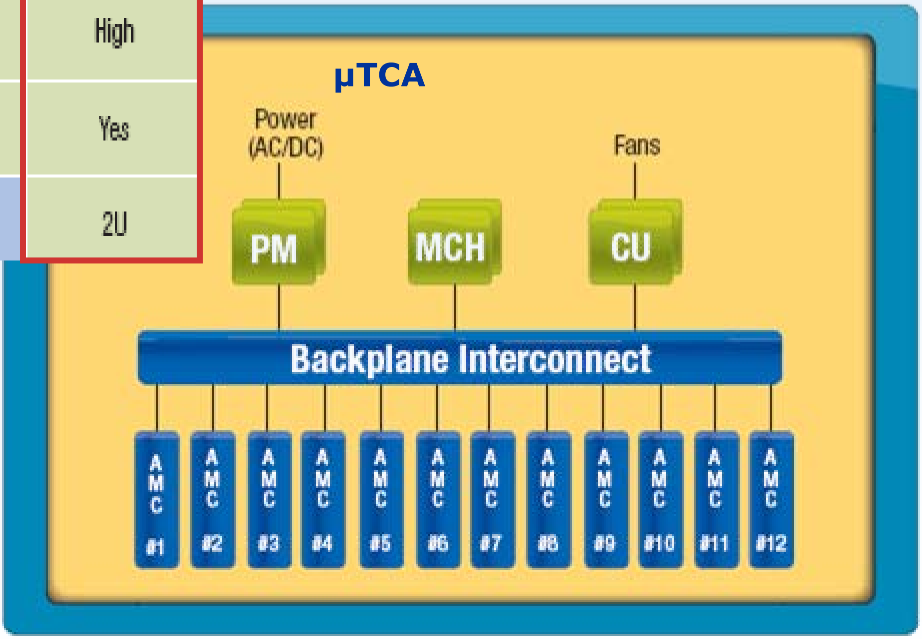
Standard organization: ANSI/VITA

Standard: VITA 46

microTCA Development

Compute Bandwidth (system)	cPCI/VME	VITA 31, 41	PICMG 2.16	ATCA	µTCA
	Low	High	High	Very High	High
Comm. Bandwidth	Low	Med	Med	Very High	High
High Availability	No	No	Yes	Yes	Yes
Form Factor	3U	6U	6U	8U	2U

microTCA (µTCA) supports redundancy management of computing resources as well as power distribution, and it is highly scalable.



*** Graphics supplied by RTC Magazine**

microTCA Ruggedization

Environmental Class	Cooling Method	Operating Temperature Class	Non-Operating Temperature Class	Temperature Cycling Class	Vibration Class	Operating Shock
EAC1	Forced Air-cooled	AC1	C1	C1	V1 ~ 2G (0.04g²/ Hz, 5 to 100 Hz)	20g
EAC2		AC2	C2	C2		
EAC3		AC3	C3	C3		
EAC4		AC1	C1	C1	V2 ~8G (0.04g²/ Hz, 100 to 1000 Hz)	
EAC5		AC2	C2	C2		
EAC6		AC3	C3	C3		
ECC1	Conduction-cooled	CC1	C1	C1	V3 ~12G (0.1g²/ Hz, 100 to 1000 Hz)	40g
ECC2		CC2	C2	C2		
ECC3		CC3	C3	C3		
ECC4		CC4	C4	C4		
ELC1	Liquid Flow-Through Cooled	LC1	C1	C1		
ELC2		LC2	C2	C2		
ELC3		LC3	C3	C3		
ELC4		LC4	C4	C4		

Hybricon Corp. ruggedized ATR enclosure

μTCA ruggedization requirements are being developed to address the environmental requirements of virtually any commercial, defense or aerospace application.

- **ANSI/VITA 47 (derived from MIL-STD-810-F), for environmental testing and compliance**
- **MIL-STD-461 for EMI/EMC requirements.**
- **MIL-STD-704 aircraft power or MIL-STD-1275 vehicle power.**

microTCA conduction cooling concept development

*** Graphics supplied by RTC Magazine**

Distributed Engine Control Subsystems

Task Focus

- Investigate the availability and application of open standards for embedded components in distributed systems
- Investigate the performance of commercially available electronic components under extreme environmental conditions
- Analyze the environmental requirements for embedded engine effectors
- Identify potential strategies for harsh environment control
- Drive applications into the high temperature electronics development effort

Smart Control Effectors

What is a "smart" sensor or a "smart" actuator?

Smart transducer: A smart transducer is a transducer that provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity. This functionality typically simplifies the integration of the transducer into applications in a networked environment. (adapted from IEEE 1451 working group)

Most people have their own concept of what "smart" means but the issue is being addressed.

IEEE 1451

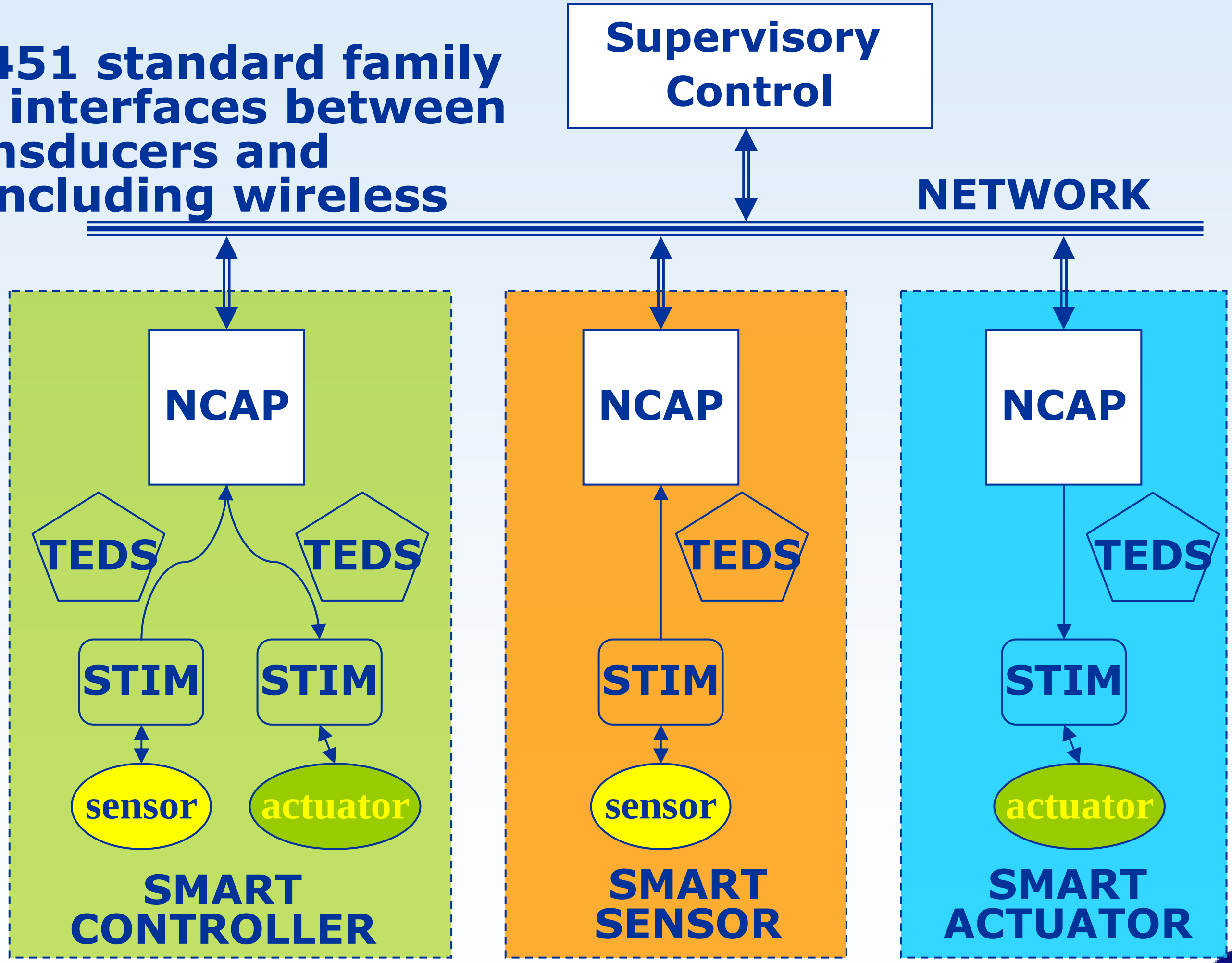
Standard for a Smart Transducer Interface for Sensors and Actuators

The objective of IEEE 1451 is to develop a smart transducer interface standard to make it easier for transducer manufacturers to develop smart devices and to interface those devices to networks, systems, and instruments by incorporating existing and emerging sensor and networking technologies. The standard interface consists of three parts.

- ***Smart Transducer Interface Module (STIM)*** – electronics to convert the native transducer signal to digital quantities.
- ***Transducer Electronic Data Sheet (TEDS)*** – a memory which contains transducer specific information such as; identification, calibration, correction data, measurement range, manufacture-related information, etc
- ***Network-capable application processor (NCAP)*** - the hardware and software that provides the communication function between the STIM and the network

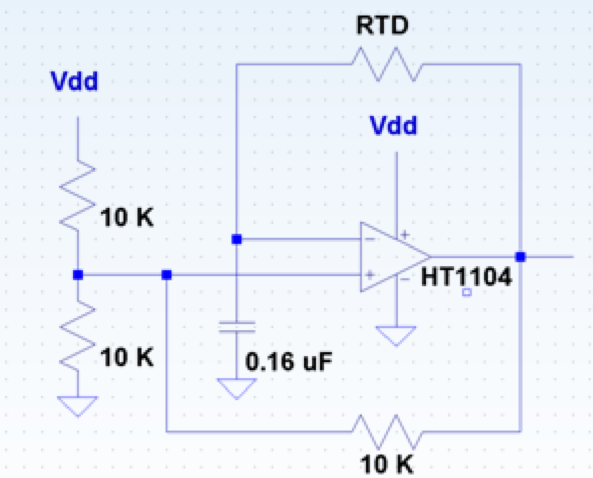
IEEE 1451

The IEEE 1451 standard family defines the interfaces between various transducers and networks, including wireless



Frequency Output Sensors

Frequency output sensors have desirable characteristics for high temperature applications. Simple relaxation oscillator circuits can be constructed from commercial high temperature (< 300 C) components to create sensors for temperature, pressure, speed, etc.

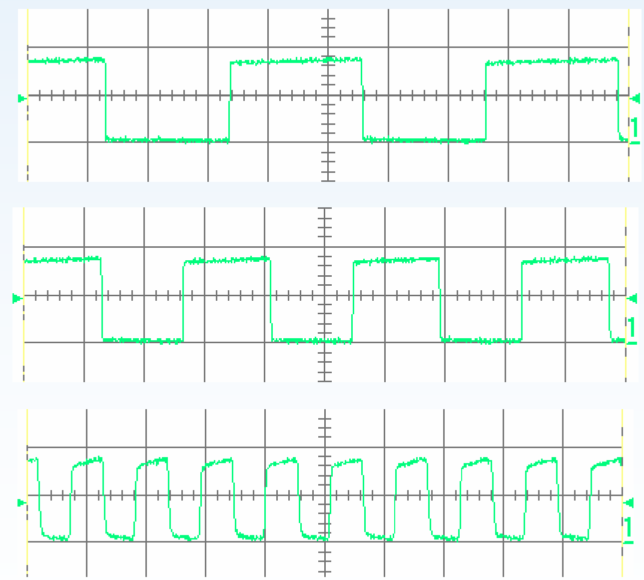


Embedded Temperature Sensor

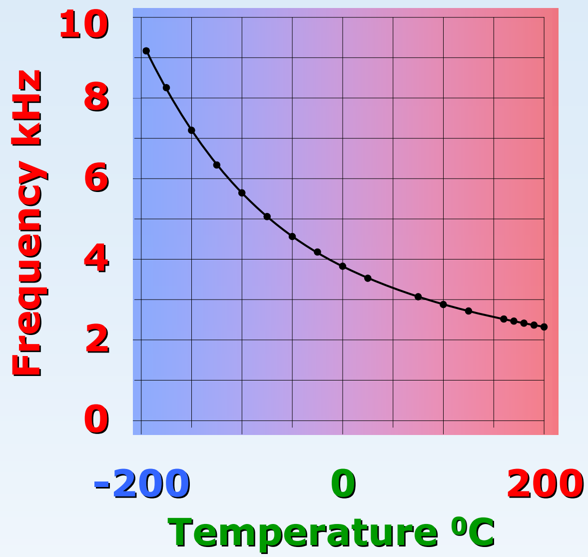
+200 C

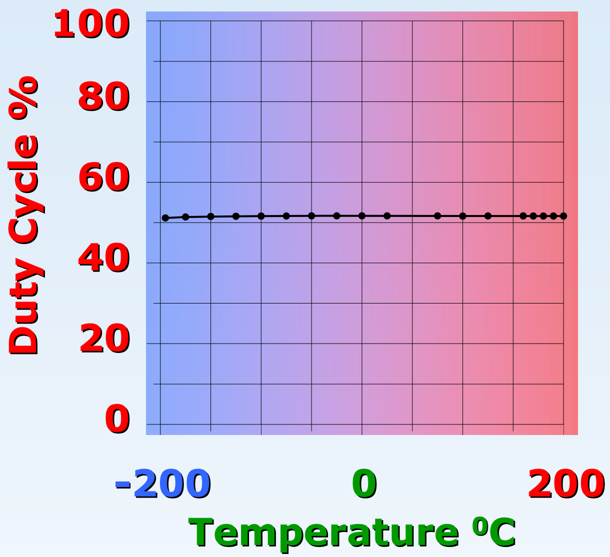
25 C

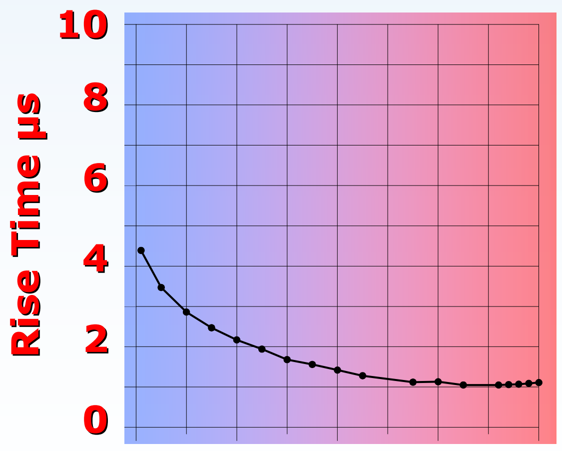
-195 C



Frequency Output Sensors



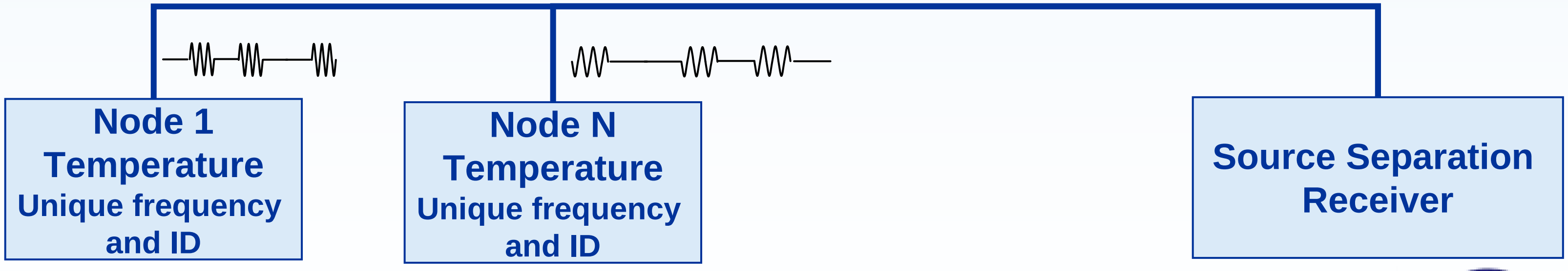




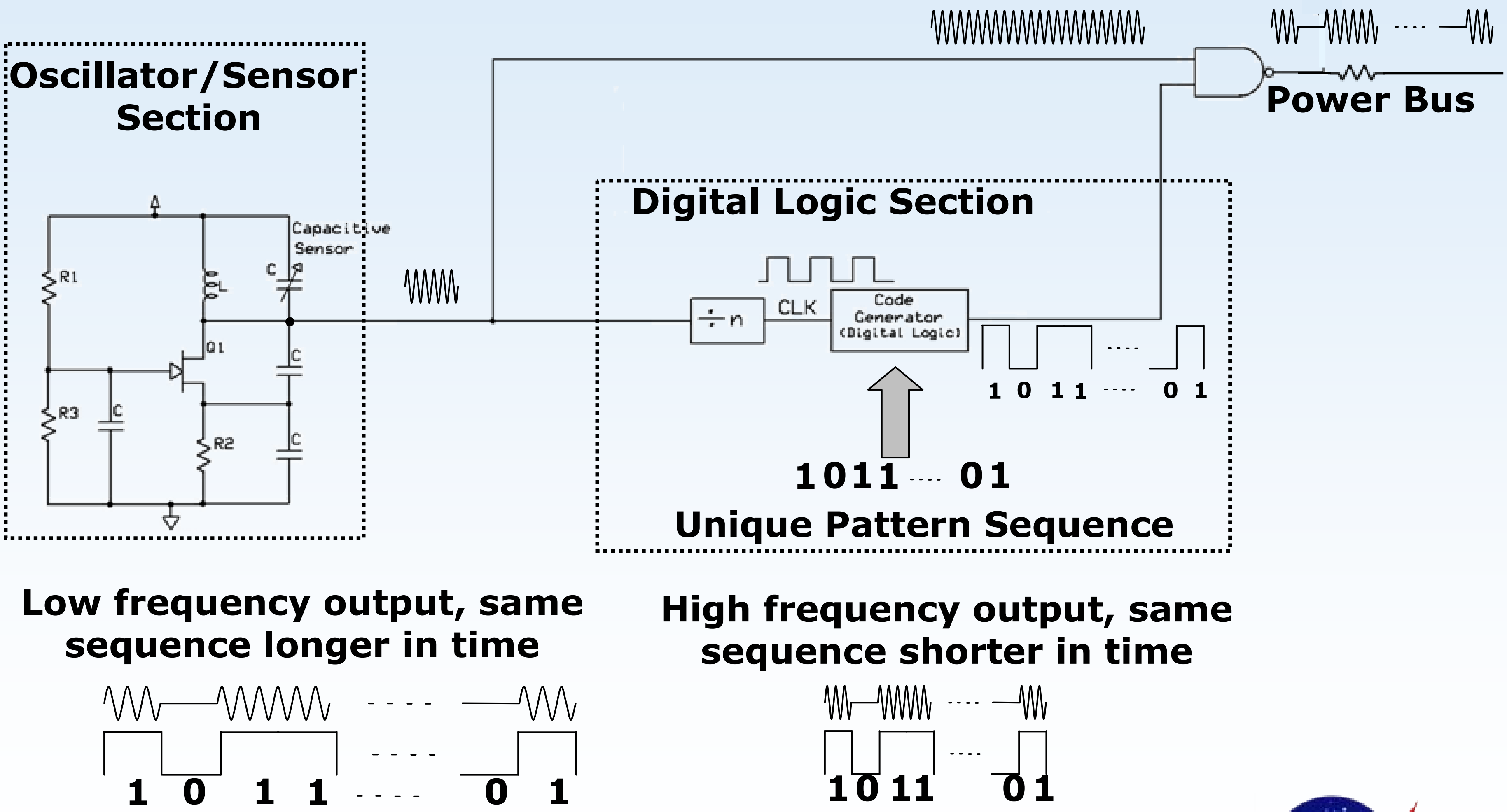
High Temperature SiC Smart Sensor Communication Network for Engine Instrumentation

New architecture for distributed sensor nodes for operation up to 500 ^{0}C

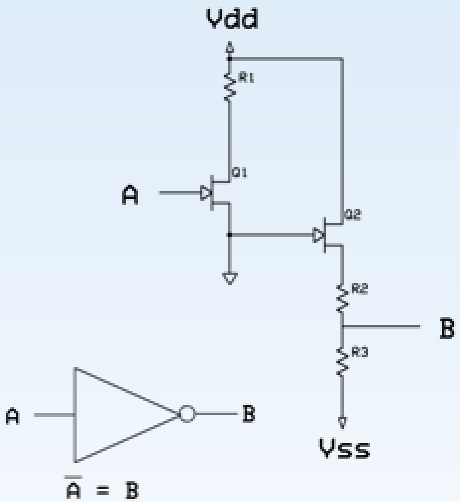
- Uses oscillators and logic gates constructed from SiC JFETs
  - Logical NOT, NAND, NOR gates and counters
  - Circuit constructs demonstrated with commercial JFETs at room temperature
- Each node produces a unique frequency signature enabling data separation on a common channel which can be wireless, wired, or over the common power bus
- Sensed parameter is transmitted as a change in frequency
- Each node superimposes a unique digital bit pattern in the frequency output to transmit device information, e.g., serial number, calibration data, etc.

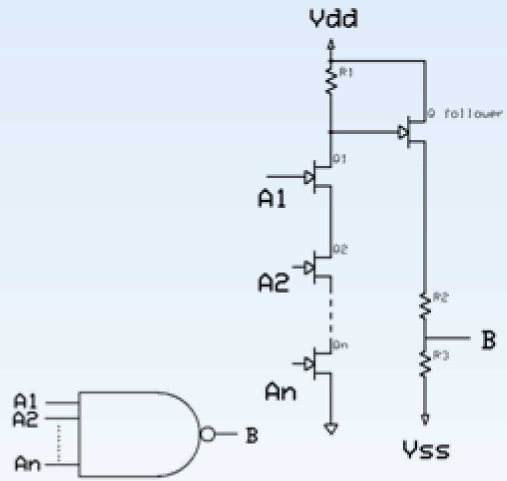


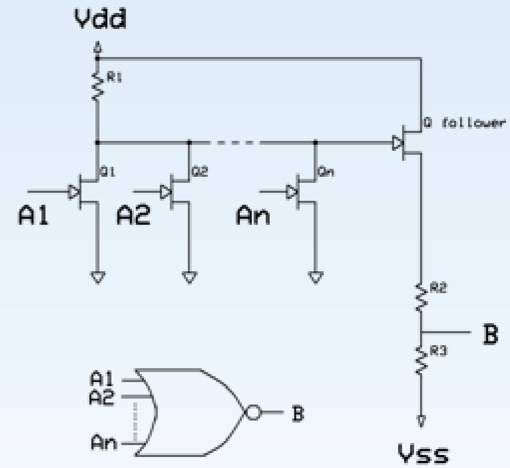
High Temperature Direct Digital Communication

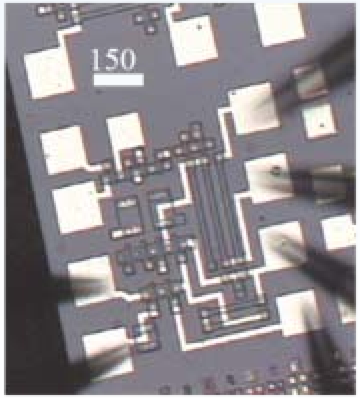


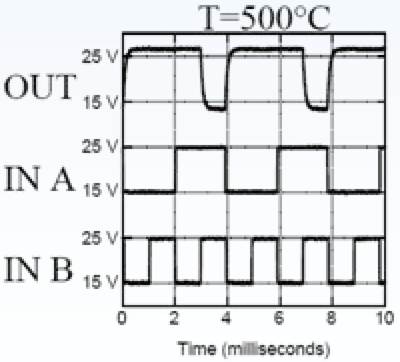
SiC JFET Digital Logic





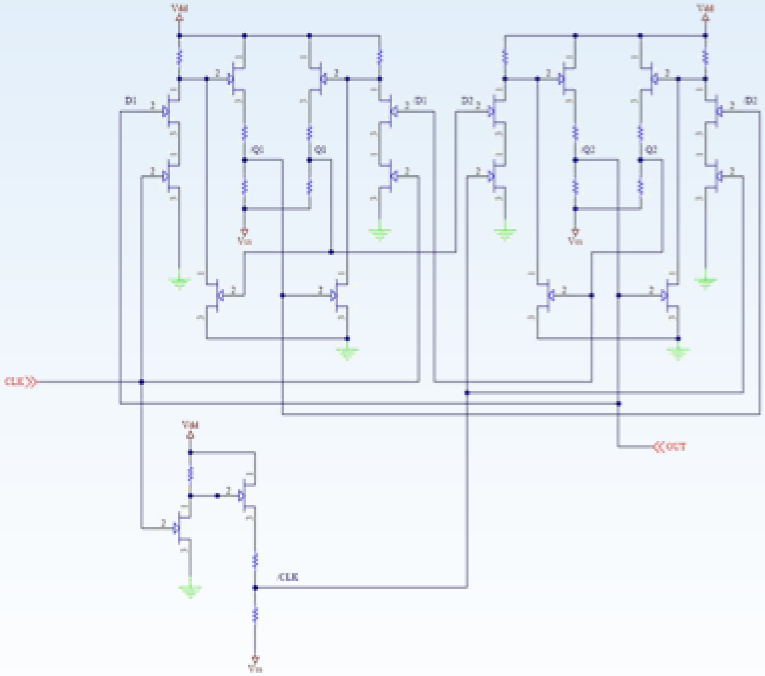


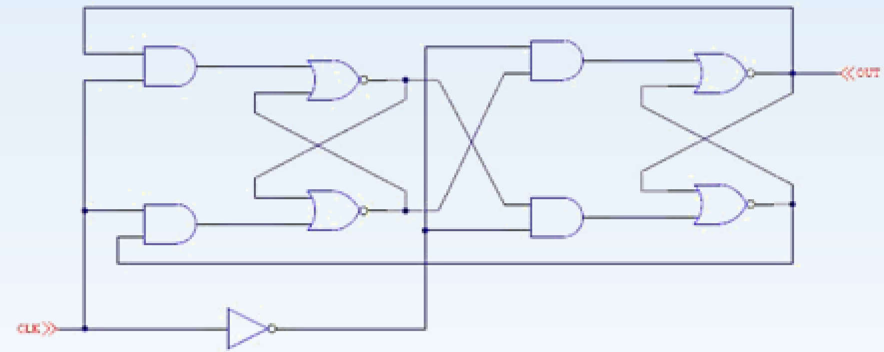


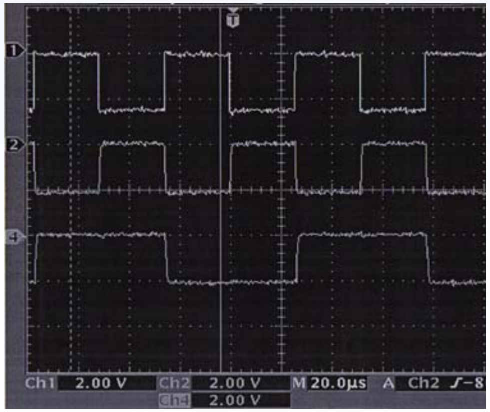


Digital Counter Using JFETs

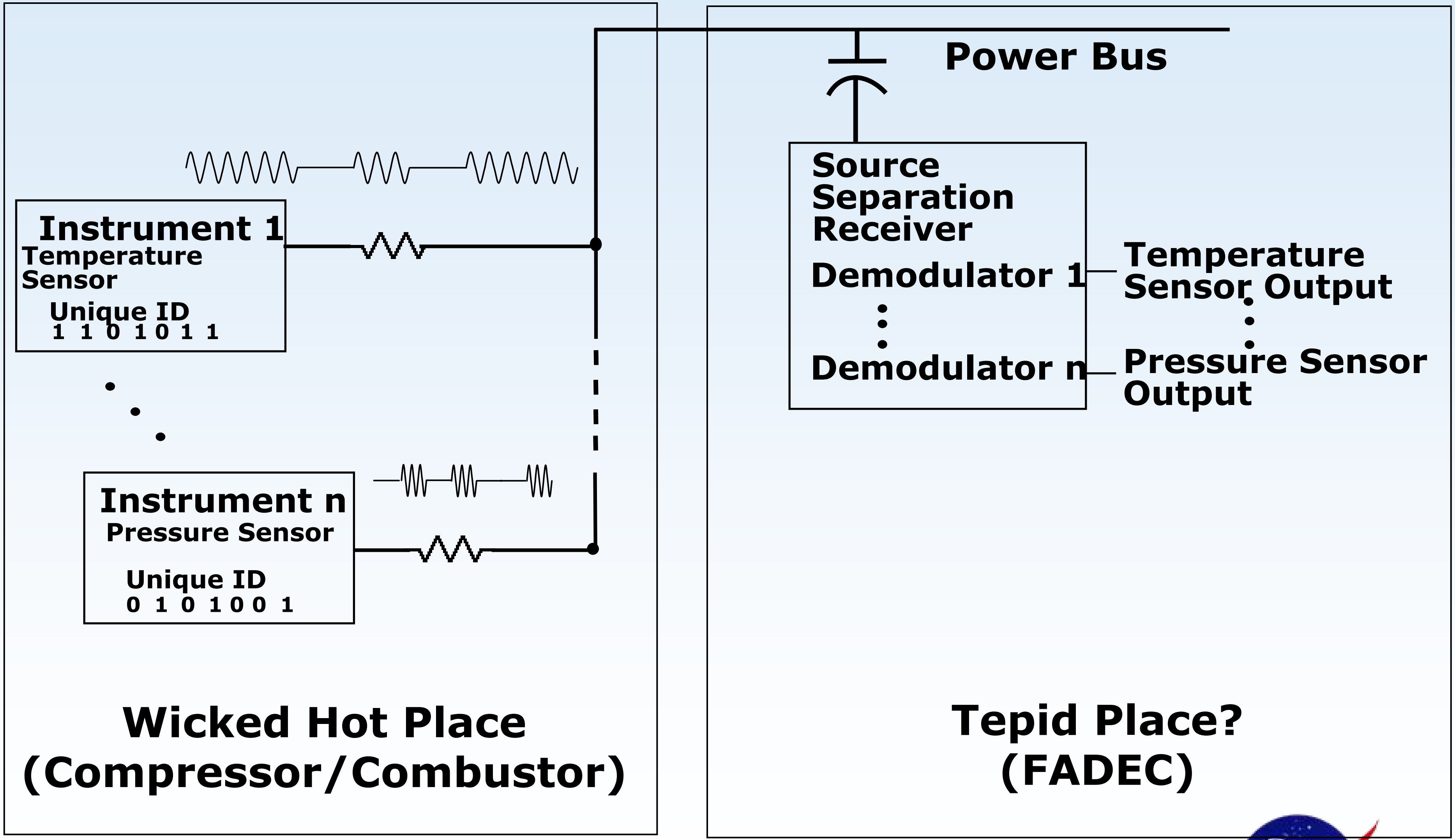
D Flip Flop constructed from commercial JFETs at room temp. using topography created for SiC Logic Gates







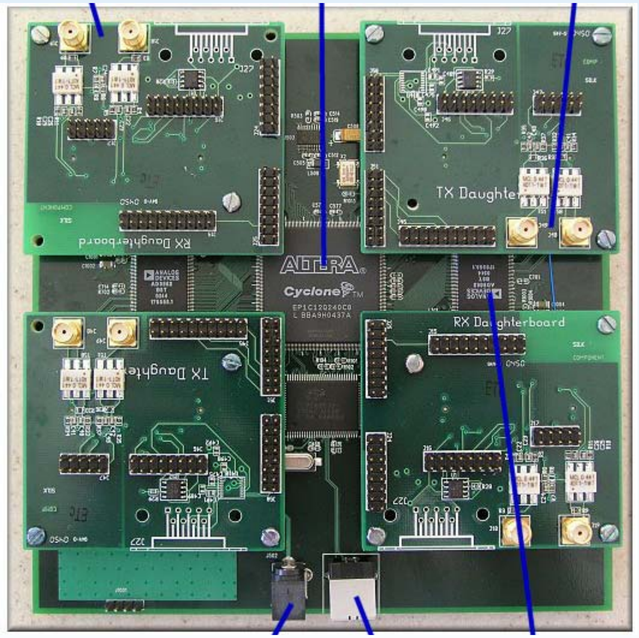
Direct Digital Communication Instrument Scenario



Software Defined Radio

Software Defined Radio (SDR) is being investigated as a possible standard interface in the FADEC (or IVHM system) as a collector of system sensory data.

SDR can be implemented for wired as well as wireless sensor application.



Universal Software Radio Peripheral (USRP) is a low cost, open source software defined radio platform in the tradition of Linux.

High Temperature Electronics & Sensors

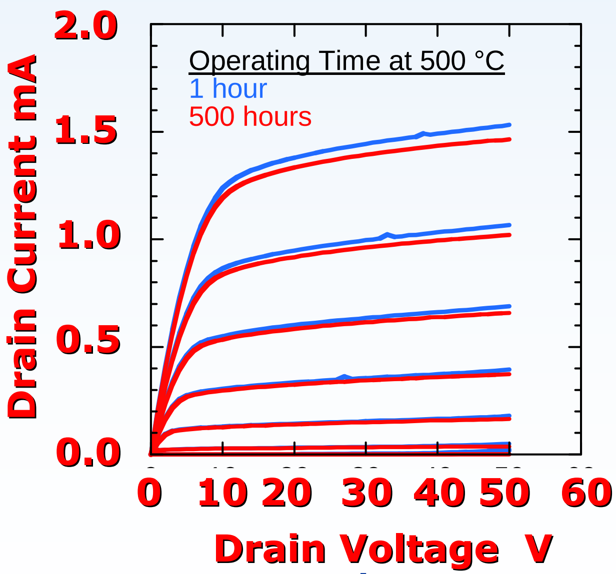
Task Focus

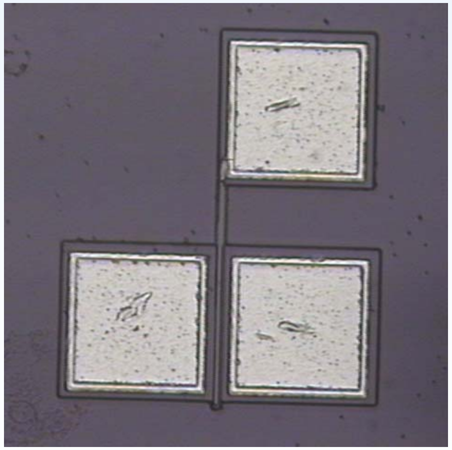
- **Develop the technologies to implement reliable, integrated electronics for high temperature applications**
  - **Stable, high temperature transistors**
  - **Multilevel interconnect structures for complex integrated circuit development**
  - **High performance packaging and interconnects for reliable, extreme environment applications**
- **Focus component development on applications developed within the DEC project**
- **Develop high temperature sensing capabilities**

Silicon Carbide Junction Field Effect Transistor

New device demonstrated at 500 ^{0}C continuous operation for over 500 hours

- Far superior turn-off characteristics than previous GRC record device
  - Enables development of feasible high temperature logic devices
- Current-voltage characteristics are very good and stable after 500 hours
  - Enables development of feasible high temperature analog devices such as amplifiers and oscillators
- Effort is a leveraged investment between Distributed Engine Controls (Subsonic Fixed-Wing) and High Temperature Wireless (IVHM)





Magnified view of unpackaged device

NASA builds a hot temperature circuit chip

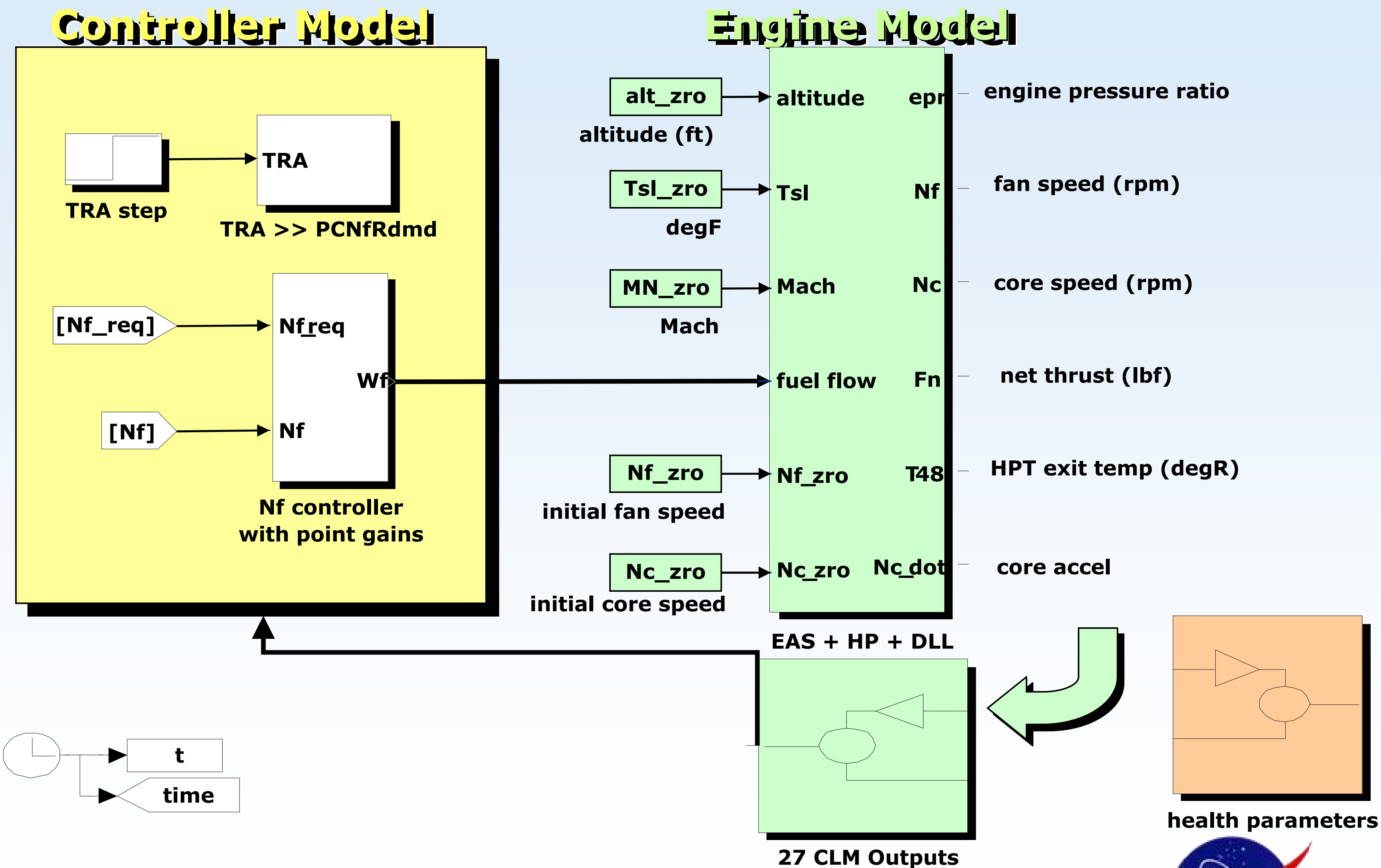
CLEVELAND, Sept. 11 (UPI) -- U.S. space agency scientists have designed and built a circuit chip that can operate for long periods in high temperature environments.

In the past, integrated circuit chips could not withstand more than a few hours of high temperatures before degrading or failing. The National Aeronautics and Space Administration's new chip exceeded 1,700 hours of continuous operation at 500 degrees Celsius (932 degrees Fahrenheit) -- a 100-fold increase over previous chips.

NASA said the new silicon carbide differential amplifier integrated circuit chip might provide benefits to anything requiring long-lasting electronic circuits in very hot environments, such as small circuitry in hot areas of jet engines as well as automotive engines.

"It's really a significant step toward mission-enabling harsh environment electronics," said Phil Neudeck, an electronics engineer at NASA's Glenn Research Center in Cleveland. "This new capability can eliminate the additional plumbing, wires, weight and other performance penalties required to liquid-cool traditional sensors and electronics near the hot combustion chamber, or the need to remotely locate them elsewhere where they aren't as effective."

Distributed Engine Control Breadboard



Opportunities for Collaboration

No funded opportunities under SFW

- **Integrated distributed system tools**
  - **Software partitioning and development**
  - **System modeling and performance analysis**
  - **System reliability modeling**
- **Engine environment requirements definition**
- **Sensor / actuator development and packaging**
- **Standards development - all types**
- **Failure modes and effects of distributed systems**
- **Flight certification requirements for distributed systems**

References

Status, Vision, and Challenges of an Intelligent Distributed Engine Control Architecture, A. Behbahani, D. Culley, et al, SAE2007-01-3859, SAE 2007 Aerotech Congress and Exhibit, Los Angeles, CA, September 17-20, 2007

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